Remote Sensing and Numerical Modeling of Suspended Sediment Dispersion in Laguna de Terminos, Campeche, Mexico

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Abstract: It is necessary to understand the physical processes at work in complex coastal lagoons in order to manage them effectively. Improved methods of data collection and analysis must be found to provide synoptic, timely hydrodynamic information because of the sheer size of some lagoons and the difficulty of acquiring *in situ* data (particularly in the tropics). This paper summarizes research to model suspended sediment distributions in Laguna de Terminos, Mexico, using 1) a coupled hydrodynamic and dispersion model and 2) analysis of Landsat Thematic Mapper data collected on November 25, 1984 and April 24, 1987. Atmospherically corrected chromaticity data derived from Thematic Mapper data were significantly correlated with modeled total suspended sediment concentrations for the two dates. Comparison between numerically modeled and remotely sensed suspended sediment maps at 1.5 x 1.5 km resolution yielded a covariation map useful for identifying areas of discrepancy between the remotely sensed data and model output.

Introduction

Coastal lagoons occupy 13% of the coastal area of the world (Barnes, 1980). In general, they exhibit high primary and secondary productivity and are of significant economic importance, particularly along tropical coastlines. Unfortunately, human, agricultural, and industrial runoff often make them eutrophic and polluted. A unified strategy is lacking for environmental management of coastal lagoons, particularly in tropical regions. Some critical requirements for management include: 1) an understanding of how coastal lagoons respond to different physical forcing functions such as tides, winds, and river discharge, and 2) an ability to predict lagoon hydrodynamics and the dispersion of suspended sediment and other constituents.

Unfortunately, long-term data sets are usually not available in tropical coastal lagoons and coastal field laboratories are either non-existent or are poorly equipped to carry out extensive field sampling. Other methods of investigating physical processes must therefore be employed. This paper describes the use of Landsat Thematic Mapper (TM) data in conjunction with a numerical hydrodynamic-dispersion model. The remotely sensed data provides synoptic information on the lagoon's water surface characteristics, which are impractical to obtain using only *in situ* data collection techniques, while the numerical simulation modeling provides a predictive capability. This study focuses on a tropical coastal lagoon in Campeche, Mexico (Figure 1); however, the methodology can be applied to similar coastal lagoon or estuarine systems.

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It is often difficult to coordinate *in situ* data collection with satellite remote sensor data collection. For example, Table 1 summarizes environmental and sensor system difficulties associated with acquiring Landsat TM data of Laguna de Terminos, Mexico. Thematic Mapper imagery of the lagoon obtained on November 24, 1984 and April 24, 1987 are displayed in Figures 2 and 3. The analysis of the November 24, 1984 TM data is summarized in Jensen et al. (1987). This paper focuses primarily on the results of analyzing the April 24, 1987 TM data and the numerical model simulations associated with this date. *In situ* hydrographic measurements collected at Laguna de Terminos from March 7-23, 1987 were used to calibrate the numerical model.

The Study Area

Laguna de Terminos encompasses an area 2,500 km^2 and borders the Gulf of Mexico at the base of the Yucatan Peninsula. It is 60 km in length with a maximum width of 25 km. The lagoon has an average depth of 3.5 m and experiences mixed, mainly diurnal tides with a mean range of 0.4 - 0.7 m (Phleger and Ayala-Castanares, 1971). The lagoon is separated from the Gulf of Mexico by Isla del Carmen, with Carmen Inlet and Puerto Real Inlet permitting water exchange between the lagoon and the Gulf (Figure 1). It is a highly productive system and serves as a breeding ground for Mexico's largest shrimp fishery (*Penaeus setiferus*) located in the adjacent gulf. Petroleum exploration in the region poses a threat to the local fisheries and the ecology of the lagoon. Effective management of the lagoon's natural resources is of great concern and requires an understanding of physical processes in the system. Only a few studies have evaluated the physical characteristics of the lagoon because of difficulty in acquiring long-term hydrographic and meteorological data and the expense and effort required to sample synoptically over the lagoon's large surface area (Gierloff-Emden, 1977; Botello, 1978; Dressler, 1981).

The regional climate is characterized by three distinct seasons: June through November is the wet season; November through March is a period of winter 'nortes' with strong winds and occasional heavy rains; and February through May is the dry season (Yanez-Arancibia and Day, 1982). The Palizada with a mean annual flow of 375 m^3/s, the Chumpan (15 m^3/s), and the Candelaria (38 m^3/s) are the three major rivers discharging into the lagoon (Figure 1). The Palizada is a distributary of the extensive Usumacinta-Grijalva River system, the largest system in Mexico (Soberon-Chavez and Yanez-Arancibia, 1985). East-southeast trade winds at an average speed of 4 m/s predominate for most of the year, although from November to March, strong winds greater than 8 m/s occasionally blow from the northwest during short-lived 'norte' conditions. The prevailing trade winds drive a tidally-averaged circulation, characterized by an inflow of Gulf water at Puerto Real Inlet and outflow of lagoon water at Carmen Inlet. This residual pattern reverses during 'norte' events (Gierloff-Emden, 1977).

In Situ Hydrographic Data Collection

Hydrographic field data were collected from 22 stations in Laguna de Terminos over the period March 7 - 23, 1987 as coincident as possible with a Thematic Mapper overflight (Figure 1). Measurements at each station included water depth, Secchi depth, surface and near bottom concentrations of suspended solids, chlorophyll *a*, salinity, turbidity, and downwelling and upwelling radiance just above the water surface using a Spectron Engineering spectroradiometer. Only 5 - 8 stations were sampled by boat per day because of the large surface area of the lagoon. Although this might seem to be a problem, previous *in situ* data collection and model runs revealed that flow and dispersion dynamics in the lagoon are sluggish, particularly in the interior where conditions are essentially constant over one to two days (Jensen et al., 1987; Kjerfve et al., 1988).

The Coupled Numerical Hydrodynamics and Dispersion Model

The hydrodynamics (circulation) model was originally developed by Blumberg (1977a,b) to simulate tidal flow in Chesapeake Bay. His model was modified extensively in this research, including the introduction of a coupled dispersion model. Whereas other hydrodynamic models have been used to analyze Laguna de Terminos (Dressler, 1981; Graham et al., 1981), no prior investigations have incorporated dispersion modeling of the lagoon and none have quantitatively evaluated information obtained from remotely sensed data.

The numerical finite difference hydrodynamics model primarily simulates the tidal flow in Laguna de Terminos, but also incorporates the effects of wind stress and fresh water input. The model is vertically integrated for use in tidal waters of relatively uniform, shallow depth. The numerical dispersion model is coupled with the circulation model to simulate concentrations of dissolved and suspended conservative constituents in the water. The circulation and dispersion models are time-varying and operate simultaneously. They were executed on a VAX 11/780 operating under VMS. The coupled circulation and dispersion model is solved numerically using a finite difference grid of Laguna de Terminos. A brief description of the mathematical formulation of the model is presented here. For additional details refer to Kjerfve et al. (1988).

The starting point for the circulation model is the set of global shallow water equations (Welander, 1957) resulting after vertical integration of the momentum balance equations. Both Blumberg (1977b) and Tee (1976) found that any simplification of the governing equations produced major changes in the simulated circulation patterns. Thus, non-linear advection, Coriolis, and friction terms are included in the momentum balance equations. Vertical integration of the x- and y-component momentum balance equations yields:

$$\delta uH/\delta t + \delta u^2H/\delta x + \delta uvH/\delta y - fvH + gH\delta\eta/\delta x = \tau^w{}_x/\sigma - k\, u(u^2 + v^2)^{1/2} \quad [1]$$

$$\delta vH/\delta t + \delta uvH/\delta x + \delta v^2H/\delta y - fuH + gH\delta\eta/\delta y = \tau^w{}_y/\sigma - k\, v(u^2 + v^2)^{1/2} \quad [2]$$

where u and v are the vertical averages of the depth-varying velocities u' and v', respectively, i.e. $u = \int u'dz/H$ and $v = \int v'dz/H$, where the limits of integration are from the bottom, $z = -h$, to the water surface, $z = \eta$, and η is the local water elevation relative to mean water; H is the total water depth defined as $H = h + \eta$; f is the Coriolis parameter; τ^w is the total wind stress decomposed into wind stresses along the x- and y- axes; and *k* is a constant friction coefficient equal to 0.0025 for all model simulations of Laguna de Terminos. For a detailed derivation of the friction coefficient refer to Kjerfve et al.(1988).

Mass must also be conserved in the hydrodynamic modeling. Because Laguna de Terminos is shallow, water density can be assumed to be unaffected by pressure. The general expression for conservation of mass can therefore be replaced with the continuity equation, vertically integrated from the bottom, -h, to the water surface, η:

$$\delta\eta/\delta t + \delta uH/\delta x + \delta vH/\delta y = 0 \qquad [3]$$

The dispersion model allowed for the calculation of salinity and total suspended solids (TSS) concentrations in Laguna de Terminos. It is based on the equation for conservation of mass applied to an arbitrary conservative constituent, C, expressed as:

$$\delta CH/\delta t + \delta uCH/\delta x + \delta vCH/\delta y - \delta HK_x\delta C/\delta x^2 - \delta HK_y\delta C/\delta y^2 = F \qquad [4]$$

where the total flux of the constituent into or out of the modeled domain is expressed as F and includes fluxes through the air-sea interface, the sediment-water column interface, exchanges between the Gulf of Mexico and Laguna de Terminos, and input from rivers entering the lagoon. This formulation of the dispersion equation employs effective dispersion coefficients, K_x and K_y, which are functions of both the longitudinal velocity and numerical grid size, i.e.

$$K_x = 0.2\ dx\ (u^2 + v^2)^{1/2} \qquad [5]$$

$$K_y = 0.2\ dy\ (u^2 + v^2)^{1/2}. \qquad [6]$$

The coupled model calculates time-averages and instantaneous values of water elevations, u and v velocities, salinity and suspended sediment concentrations, and presents the results as maps with resolution cells of 1.5 km by 1.5 km.

Model Calibration and Simulation

Inputs to the model included: 1) phase and amplitude of the dominant tidal constituents; 2) wind stress; 3) constituent concentrations along the open boundaries; 4) discharge of the major rivers; 5) friction and dispersion coefficients; 6) upstream constituent concentrations for the major rivers; 7) initial water elevations at the two inlets; and 8) bathymetry. Calibration of the numerical model was accomplished by adjusting boundary conditions and other model inputs to attain a best model fit to the *in situ* data collected at the twenty-two (22) locations. This was an iterative process, drawing on available data, reasonable *a priori* estimates of actual conditions, and past experience. The procedure was hierarchal in that it proceeded by first assigning the best known parameters and then estimating the parameters with the greatest uncertainty.

Phases and amplitudes of the dominant tidal constituents at the two ocean inlets were obtained from hydrographic chart S. M. 1611 (Secretaria de Marina, 1979). Both the field sampling and the April 24, 1987 model simulation were forced with these values (Table 2), which are for a mixed, mainly diurnal tide with 1.0 hr phase lag from Carmen Inlet to Puerto Real Inlet. The model simulation of the field sampling period was forced with a fluctuating wind regime, from NW winds, to ESE, to NW, and ending with calm winds. River discharges input to the model were based on flow calculations made in the Candelaria River and historical monthly discharge estimates over the period 1970-1980 (Soberon-Chavez and Yanez-Arancibia, 1985). Initial boundary concentrations of salinity and suspended sediments at the river mouths and the two inlets were taken from the field data and then adjusted after several calibration runs.

Calibration runs were executed over the period February 19 - March 23, 1987. This starting time was chosen rather than March 7, 1987 because the model requires at least 14 tidal cycles before steady-state conditions are reached. Initial boundary conditions for the calibrated numerical simulation of the field sampling period are listed in Table 3.

Because there were no real-time meteorological data available for the April 24, 1987 model simulation coincident with the Landsat TM data, it was necessary to use historical mean monthly meteorological data from Merida, Mexico. According to these data, the most common regime during April was ESE winds blowing at 3 m/s. Also, no daily discharge estimates were available for the rivers; therefore, the model was forced with 10-year average historical monthly discharge estimates. Initial boundary conditions input to the model were those from the field data calibration run. Model predictions of water velocity streamlines and total suspended solids (TSS) concentrations on April 24, 1987 at the time of the Landsat TM overflight are shown in Figure 4.

Remote Sensing of Suspended Sediment Using Landsat TM Data

Landsat TM data acquired on November 25, 1984 and April 24, 1987 were used to characterize the spatial distribution of suspended sediment in Laguna de Terminos. The data were geometrically rectified to a longitude/latitude coordinate system using ground control points and a nearest neighbor resampling algorithm. Pixel size after resampling was 30 x 30 m. Natural color composites (TM bands 3, 2, 1 filtered with red, green, and blue light, respectively) of the study area after rectification are shown in Figures 2a and 3. Direct comparison between bands was accomplished by normalizing all bands to the same scale. Original brightness values were converted to radiance values [mW / (cm^2 sr um)] using the bias and gain factors in the tape header (NASA, 1984). These radiance values were then normalized by associated bandwidths using techniques described in Markham and Baker (1985).

Generation of suspended sediment estimates using the November 25, 1984 Landsat TM data and comparison of these estimates to the model predictions are discussed in Jensen et al. (1987). This initial research used an atmospheric correction strategy incorporating a radiative transfer model developed by Turner and Spencer (1972) and Turner (1978), and an iterative method of deriving model input parameters (Ahern et al., 1977; Verdin, 1985). The atmospheric correction strategy produced a reflectance image representing the intrinsic water properties at the time of the overpass, independent of changes in sun and sensor geometries and illumination conditions. For example, the original TM natural color composite image (bands 3, 2, 1 displayed in red, green, and blue) and the atmospherically corrected TM natural color reflectance image are shown in Figures 2a and 2b, respectively. There was a clear improvement in image contrast and clarity. Furthermore, the atmospheric correction of the original TM data improved the correlation between the model simulation and the remotely sensed data (Jensen et al., 1987).

In order to apply the path radiance atmospheric correction to the April 24, 1987 TM data, it was necessary to locate an area of water that contained little or no suspended sediment. Unfortunately, this was not possible because of offshore clouds and overall high turbidity in the lagoon. Therefore, the analysis of the April 24, 1987 TM data to detect suspended sediment was based on other transformations found to be of value in previous research (Jensen et al., 1987), including a chromaticity transformation of the data, a corrected chromaticity transformation incorporating a heterogeneous haze component, and a principal component transformation.

The Chromaticity Transformation: Chromaticity transformations have been shown to correlate with water quality measurements, i.e. Secchi disc depth and total suspended sediments (Alfoldi and Munday, 1978; MacFarlane and Robinson, 1984; Lindell et al., 1985). Chromaticity coordinates were derived for each data point in the imagery using the TM visible bands (1, 2, and 3) and a combination of visible and near infrared bands (2, 3, and 4) following the procedures described in Alfoldi and Munday (1978). In addition, the chromaticity techniques were extended to correct for a heterogeneous atmospheric haze component (Munday, 1974; Alfoldi and Munday, 1978). This correction assumed that an increase in the haze content would move any chromaticity point towards the white point (a chromaticity point depicting equal radiance in all three bands). A radial shift along a line connecting the white point and the data chromaticity coordinates defined the dominant color.This color coordinate can produce estimates of a dominant water quality parameter.

A plot of the two chromaticity coordinates (bands) derived from the visible and near infrared TM bands (2, 3, and 4) is shown as a locus of points closely centered around the white point indicating a dominance by atmospheric haze (Figure 5a). An image of these data is not shown. A plot of the atmospherically corrected chromaticity data is shown in Figure 5b. The atmospherically corrected chromaticity image is shown in Figure 5c. Both the original chromaticity data and the atmospherically corrected chromaticity data were used in subsequent analyses.

Principal Components Analysis: A principal component analysis of the normalized, Landsat TM bands 1-4 was produced using techniques summarized in Collins and Pattiaratchi (1984) and Jensen (1986).

Comparison Between Numerical Model and Landsat TM Generated Suspended Sediment Distribution

The spatial distribution of total suspended solids on April 24, 1987 predicted by the numerical model is shown in isoline format in Figure 4b and as a continuous image in Figure 6a. The brighter the 1.5 x 1.5 km model cell, the greater the total suspended solids concentration. The high TSS concentrations in the western part of the lagoon were due, in part, to the high input of fluvial sediments from the Palizada River. In addition, inflow of ocean water at Carmen inlet also contributed to increased TSS concentrations by carrying fluvial sediments from the ebb tidal delta into the lagoon (Figures 3, 4 and 5b).

The *in situ* data from the twenty-two (22) sample sites within Laguna de Terminos were used to calibrate the model (Figure 1). At each site, a mean suspended sediment concentration (ppm) was extracted from the numerical model output. Also, a mean value was obtained from each of the images created from the normalized TM image data using a 15 by 15 pixel window centered at each sample location site. Total suspended solids model output at the 22 *in situ* locations was then correlated with 1) radiance values from TM bands 1, 2, 3, and 4; 2) brightness values from principal components 1, 2, 3 and 4; 3) brightness values from raw chromaticity coordinates (bands) 1 and 2; and 3) brightness values from the atmospherically corrected chromaticity images.

A summary of the correlation between the remote sensing derived parameters and the modeled suspended sediment concentrations is found in Table 4. Bands 1 and 2 of the original TM data exhibited a significant ($p < 0.05$) relationship with the modeled TSS estimates, with band 1 explaining the most variance (61%). The next best prediction was associated with principal component 4, which explained 73% of the modeled TSS variance. The chromaticity transformation increased this predictive capability to 77% based on an analysis of TM bands 2, 3, and 4, versus 60% when using TM bands 1, 2, and 3. A slightly higher explanation (79%) was attained by using the atmospherically corrected chromaticity coordinate associated with TM bands 2, 3, and 4. A scattergram showing the relationship between modeled suspended sediment and the atmospherically corrected chromaticity data for the 22 sample locations is shown in Figure 7. This was a significant improvement over the best results obtained using the November 25, 1984 TM data (45%) where chromaticity coordinates were derived from the path radiance atmospherically corrected TM data (Jensen et al., 1987). *In situ* data were not available to calibrate a model simulation of the November 25, 1984 TM data, but were available to calibrate the April 24, 1987 model run. This resulted in an improved relationship between the model's prediction of TSS and the remotely sensed data. An even higher correlation between the transformed TM data and simulated TSS concentrations may have been obtained with *in situ* data collected simultaneously with the Landsat overpass. Also, part of the unexplained variance may be due to the inability of the model to account for wave resuspension of bottom sediment.

The coupled hydrodynamics and dispersion model allowed a *spatial* comparison to be made between the modeled TSS concentrations (Figure 6a) and a spatially degraded atmospherically corrected chromaticity image at the 1.5 x 1.5 km spatial resolution (Figure 6b). Using techniques summarized in Davis (1986), the covariance was computed between the modeled TSS distribution and the atmospherically corrected chromaticity data produced using TM bands 2, 3, and 4 (Figure 7b), resulting in a covariance image (Figure 6c). The brighter the tone the higher the covariation and vice versa. The highest agreement was within the western part of the lagoon, associated with high inputs of suspended sediment from the Palizada River and Carmen Inlet. A high covariation was also found within the north central area of the lagoon where the water contained low TSS concentrations.

Summary

The spatial distribution of total suspended solids in a tropical coastal lagoon were modeled using a coupled hydrodynamic-dispersion model and transformed Thematic Mapper data. TSS concentrations measured at 22 field sites were used to calibrate the model. The model was then used to simulate the TSS distribution at the time of the April 24, 1987 TM overpass. Statistical comparisons were made between the model prediction of TSS and original TM data, chromaticity data, and principal component transformations at each of the 22 field sampling locations. An atmospherically corrected chromaticity transformation of the TM data that assumed a heterogeneous haze component accounted for 79% of the modeled TSS variance. An innovative method that generated a covariance image was then used to compare the spatial distribution of the modeled and remote sensing derived TSS estimates. In coastal lagoon/estuarine systems where long-term hydrographic data are meager or unavailable, the techniques described here may be a feasible alternative for estimating and predicting circulation and dispersion characteristics. Furthermore, the integration of remotely sensed data reduces the amount of *in situ* data collection necessary for calibration and verification of numerical models.

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References

Ahern, F. J., D. G. Goodenough, S., C. Jain, and Rao, V. R. (1977), Use of clear lakes as standard reflectors for atmospheric measurements, ***Proceedings of the Eleventh International Symposium on Remote Sensing of Environment***, 731-755.

Alfoldi, T. T., and Munday, J. C., Jr. (1978), Water quality analysis by digital chromaticity mapping of Landsat data. ***Canadian Journal of Remote Sensing***, 4(2):108-126.

Barnes, R. S. K. (1980), ***Coastal Lagoons***, Cambridge University Press, 106 p.

Blumberg, A. F. (1977a), Numerical tidal model of Chesapeake Bay, ***Journal of the Hydraulics Division***, ASCE 103:1-10.

Blumberg, A. F. (1977b), On the dynamic balance of the Chesapeake Bay waters, ***Chesapeake Science***, 18:319-323.

Botello, A. V. (1978), Variacion de los parametros hidrologicos en las epocas de sequia y lluvia (Mayo y Noviembre, 1974) en la Laguna de Terminos, Campeche, Mexico, ***Anales del Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico***, 5(1):159-178

Collins, M. and Pattiaratchi, C. (1984), Identification of suspended sediment in coastal waters using airborne thematic mapper data, ***International Journal of Remote Sensing*** 5(4): 635-657.

Davis, J. C. (1986), ***Statistics and Data Analysis in Geology***, John Wiley & Sons, 447-461 .

Dressler, R. (1981), Investigacion sobre mareas y efectos del viento en la Laguna de Terminos (Mexico), mediante un modelo hidrodinamico-numerico, ***Informe Tecnicio, CICESE***, Ensenada, Baja California, Mexico, 82:01.

Gierloff-Emden, H. G. (1977), Laguna de Terminos and Campeche Bay, Gulf of Mexico: water mass interaction, lagoonal oceanic, visible due to sediment laden waters, in ***Orbital Remote Sensing of Coastal and Offshore Environments, A Manual of Interpretation***, W. de Gryter (Ed.), Berlin, 77-89.

Graham, D. S., Daniels, J. P., Hill, J. M., and Day, J. W. (1981), A preliminary model of the circulation of Laguna de Terminos, Campeche, Mexico, Anales del Instituto de Ciencias del Mar y Limnologia, ***Universidad Nacional Autonoma de Mexico***, 8:51-62.

Jensen, J. R. (1986). *Introductory Digital Image Processing: A Remote Sensing Perspective,* Prentice-Hall, Englewood Cliffs, NJ , 151-157.

Jensen, J. R., Ramsey, E. W., Kjerfve, B., Magill, K., and Sneed, J. (1987), Application of Landsat Thematic Mapper data to assess suspended sediment dispersion in a coastal lagoon, ***Proceedings of the Fall Meeting of the American Society for Photogrammetry and Remote Sensing***, 26-35.

Lindell, L. T., Steinvall, O., Jonsson, M., and Claesson, Th. (1985), Mapping of coastal water turbidity using Landsat imagery. ***International Journal of Remote Sensing*** 6(5):629-642.

Kjerfve, B., Magill, K. E., and Sneed, J. E. (1988), Modeling of circulation and dispersion in laguna de Terminos, Campeche, Mexico, in ***Ecology of the Southern Gulf of Mexico***

with Special Reference to the Terminos Lagoon Region, A. Yanez-Arancibia (Ed.), Universidad Nacional Autonoma de Mexico, Mexico, in press.

MacFarlane, G. N. and Robinson, I. S. (1984). Atmospheric correction of Landsat MSS data for a multidate suspended sediment algorithm. ***International Journal of Remote Sensing*** 5(3):561-576.

Markham, R. L. and Barker, J. L. (1985), Spectral characteristics of the Landsat Thematic Mapper sensors, ***International Journal of Remote Sensing*** 6:697-716.

Munday, J. C., Jr. (1974), Lake Ontario water mass delineation from ERTS-1 ***Proceedings of the Ninth International Symposium on Remote Sensing of Environment***, 1355-1368.

NASA, 1984. ***A Prospectus for Thematic Mapper Research in the Earth Sciences***. Technical Memorandum #86149. U.S. Government Printing Office, Washington, D.C.

Phleger, F. F. and Ayala-Castanares, A. (1971), Processes and history of Terminos Lagoon, Mexico, ***American Association of Petrology and Geology Bulletin*** 55(12): 2130-2140.

Secretaria de Marina (1979), ***Hydrographic Chart No. S.M. 1161***, Laguna de Terminos y Proximidades, Mexico-Costa Este.

Soberon-Chavez, G. and Yanez-Arancibia, A. (1985), Control ecologico de los peces demersales: variabilidad ambiental de la zona costera y su influencia en la producion natural de los recursos pesqueros, in ***Recursos Pesqueros Potenciales de Mexico: la Pesca Acompanante del Camaron***, A. Yanez-Arancibia (Ed.) Prog. Univ. de Alimentos, Inst. Cienc. del Mar y Limnol., Inst. Nal. de Pesca, UNAM, Mexico, 399-486.

Tee, K. -T. (1976), Tide induced residual current, a 2-D non-linear numerical tidal model, ***Journal of Marine Research*** 34:603-628.

Turner, R. E. (1978), Elimination of atmospheric effects from remote sensing data, in ***Proceedings of the Twelfth International Symposium on Remote Sensing of Environment***, 783-793.

Turner, R. E. and Spencer, M. M. (1972), Atmospheric model for correction of spacecraft data, in ***Proceedings of the Eighth International Symposium on Remote Sensing of Environment***, 895-934.

Verdin, J. P. (1985). Monitoring water quality conditions in a large Western reservoir with Landsat imagery. ***Photogrammetric Engineering and Remote Sensing*** 51(3): 343-353.

Welander, P. (1957), Wind action on a shallow sea; generalizations of Ekman's theory, ***Tellus*** 9:45-52.

Yanez-Arancibia, A. and Day, J. R., Jr. (1982), Ecological characterization of Terminos Lagoon, a tropical lagoon estuarine system in the southern Gulf of Mexico, ***Oceanological Acta,*** Proceedings, International Symposium on Coastal Lagoons, 431-440.

Table 1. Landsat Thematic Mapper (TM) Data Sets and *In Situ* Sampling Dates Used to Model Suspended Sediment in Laguna de Terminos, Campeche, Mexico

Thematic Mapper Data of Laguna de Terminos	*In Situ* Data Collected	Modeling Performed
1. November 25, 1984	none available	Yes, based on historical data[1]
2. March 12, 1986 • cloud cover over lagoon	March 9-16, 1986	No, TM not available
3. March 9, 1987 • data collected but not transmitted to TDRSS	March 7-23, 1987	No, TM not available
3. April 24, 1987	March 7-23, 1987	Yes, based on March *in situ* data
4. May 26, 1987 • cloud cover over lagoon	March 7-23, 1987	No, too much cloud cover

[1]Results are presented in Jensen et al. (1987).

Table 2. Tidal Input Parameters for the Hydrodynamic-Dispersion Model Simulations of Laguna de Terminos, Mexico

	Amplitude (m)	Phase (G)	Node Factor	Equilibrium Argument	Period (hrs)
March 7-23 and April 24, 1987					
Carmen Inlet					
K1	0.119	317.0	1.112	9.2	23.93
O1	0.115	318.1	1.182	330.7	25.82
M2	0.076	82.8	0.964	339.6	12.42
S2	0.020	21.0	1.000	0.0	12.00
Puerto Real Inlet					
K1	0.120	288.4	1.112	9.2	23.93
O1	0.138	298.7	1.182	330.7	25.82
M2	0.111	37.2	0.964	339.6	12.42
S2	0.018	11.3	1.000	0.0	12.00

Table 3. Initial Boundary Conditions for the Model Simulations.

	Discharge (m^3/s)	Total Suspended Solids (ppm)	Salinity (ppt)
March 7-23, 1987 (winds ESE at 3 m/s; NW at 6 m/s; calm)			
Rio Palizada	160.0	75	0.05
Rio Chumpan	3.5	75	0.05
Rio Candelaria	18.0	75	0.05
Carmen Inlet	-	60	28.00
Puerto Real Inlet	-	45	30.00
April 24, 1987 (winds ESE at 3 m/s)			
Rio Palizada	120.0	75	0.05
Rio Chumpan	3.0	75	0.05
Rio Candelaria	16.0	75	0.05
Carmen Inlet	-	60	28.00
Puerto Real Inlet	-	45	30.00

Table 4. Correlations Between Modeled Suspended Sediment Concentrations and Remote Sensing Derived Parameters

Parameter	r	Adj r^2	Prob>F
Original Data			
Landsat TM Band 1	0.6183	0.3823	0.0013
Landsat TM Band 2	0.3975	0.1580	0.0379
Landsat TM Band 3	0.3274	0.1072	0.0752
Landsat TM Band 4	0.1967	0.0387	0.6459
Chromaticity			
• Using TM Bands 1, 2, and 3			
Chromaticity Coordinate 1	0.7766	0.6031	0.0001
Chromaticity Coordinate 2	0.3764	0.1417	0.0473
• Using TM Bands 2, 3, and 4			
Chromaticity Coordinate 1	0.5777	0.3337	0.0029
Chromaticity Coordinate 2	0.8779	0.7708	0.0001
Atmospherically Corrected Chromaticity			
• Using TM Bands 1, 2, and 3	0.3832	0.1469	0.0441
• Using TM Bands 2, 3, and 4	0.8933	0.7979	0.0001
Principal Components Analysis			
Principal Component 1	0.0346	0.0012	0.3232
Principal Component 2	0.6635	0.4402	0.0005
Principal Component 3	0.1229	0.0151	0.4165
Principal Component 4	0.7273	0.5291	0.0001

Figure Captions

FIGURE 1. Laguna de Terminos is located adjacent to the Gulf of Mexico in Campeche, Mexico. The major tributaries include the Palizada, Chumpan, and the Candelaria Rivers. Twenty-two (22) *in situ* sampling locations and the bathymetry of the area are annotated.

FIGURE 2. (A) Landsat Thematic Mapper color composite of the Laguna de Terminos study area obtained on November 25, 1984. Bands 3, 2 and 1 are displayed in red, green, and blue, respectively. (B) An atmospherically corrected color composite of the study area. All data are geometrically corrected.

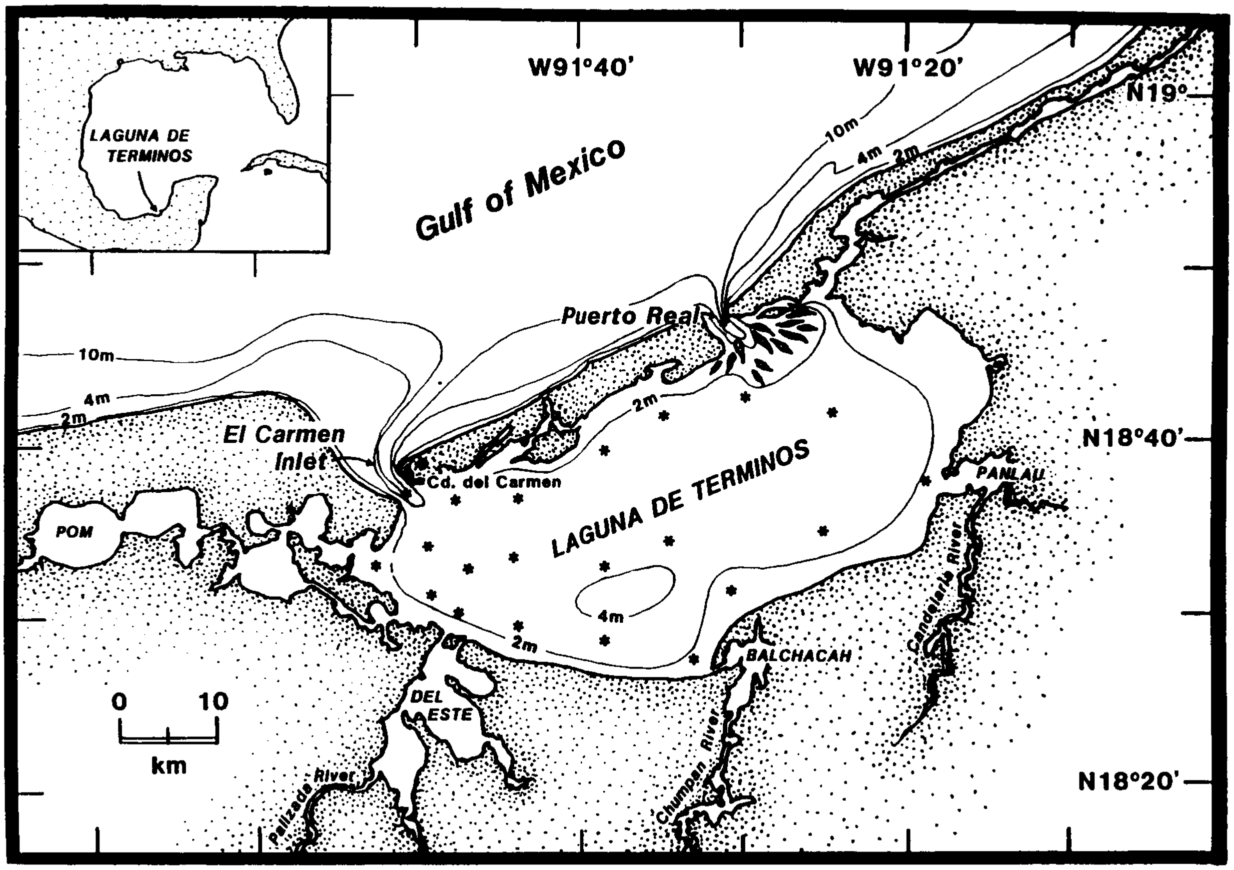
FIGURE 3. Landsat Thematic Mapper color composite of the Laguna de Terminos study area obtained on April 24, 1987 (bands 3, 2, and 1 displayed in red, green, and blue, respectively). The land was masked out to facilitate the computation of various transformations of the raw remote sensor data located within the lagoon.

FIGURE 4. Hydrodynamic-dispersion model simulation of (A) water velocity streamlines, and (B) total suspended solids (ppm) for Laguna de Terminos on April 24, 1987, 15:52 hrs (GMT). The model was forced with winds from the ESE at 3 m/s.

FIGURE 5. (A) A plot of coordinates (bands) 1 and 2 of the chromaticity data produced from April 24, 1987 Landsat Thematic Mapper using bands 2, 3, and 4. (B) A plot of coordinates (bands) 1 and 2 of the atmospherically corrected chromaticity data from April 24, 1987 Landsat Thematic Mapper data using bands 2, 3, and 4. (C) A display of the atmospherically corrected chromaticity image using an inverse ROYGBIV logic, i.e. red depicts the highest suspended sediment concentration while violet is the lowest.

FIGURE 6. (A) A raster version of the numerically modeled total suspended sediment distribution in Laguna de Terminos on April 24, 1987 at 15:52 hrs (GMT) shown in Figure 4B. The model functions with 1.5 x 1.5 km cells. (B) The atmospherically corrected chromaticity data shown in Figure 5C were spatially degraded to the 1.5 x 1.5 km resolution cell size of the model. (C) A map of the covariance between the modeled suspended sediment distribution (6A) and the corrected chromaticity data (6B). The greater the covariation, the brighter the cell.

FIGURE 7. A scatterplot depicting the association between atmospherically corrected chromaticity data derived from Landsat Thematic Mapper data and the modeled total suspended sediment concentrations for twenty-two (22) sites located within Laguna de Terminos, Mexico, on April 24, 1987.



W91°40'
W91°20'
N19°
N18°40'
N18°20'
LAGUNA DE TERMINOS
Gulf of Mexico
Puerto Real
El Carmen Inlet
Cd. del Carmen
LAGUNA DE TERMINOS
10m
4m
2m
POM
PANLAU
BALCHACAH
DEL ESTE
Palizada River
Chumpan River
Candelaria River
0 10
km

Fig 1

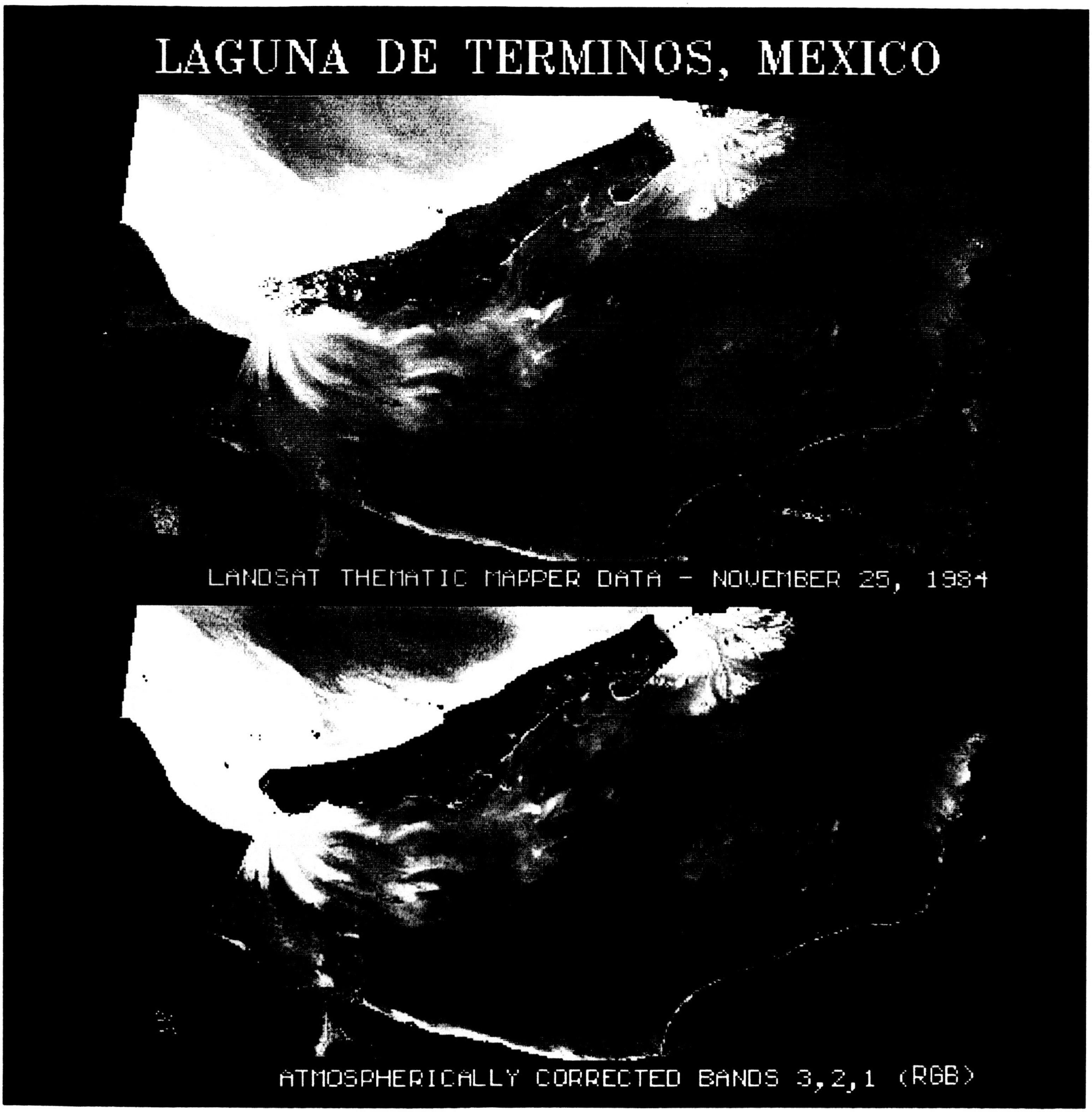
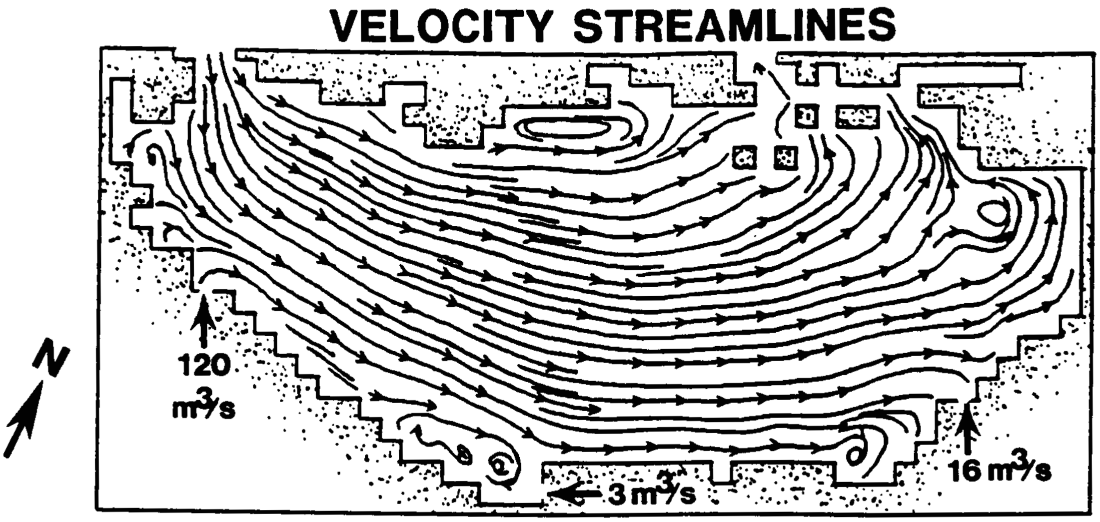

LAGUNA DE TERMINOS, MEXICO
LANDSAT THEMATIC MAPPER DATA - NOVEMBER 25, 1984
ATMOSPHERICALLY CORRECTED BANDS 3,2,1 (RGB)

Fig 2- A,B

LAGUNA DE TERMINOS, MEXICO

LANDSAT THEMATIC MAPPER DATA - APRIL 24, 1987
BANDS 3,2,1 (RGB)

Fig 3


VELOCITY STREAMLINES
120 m3/s
3 m3/s
16 m3/s
N

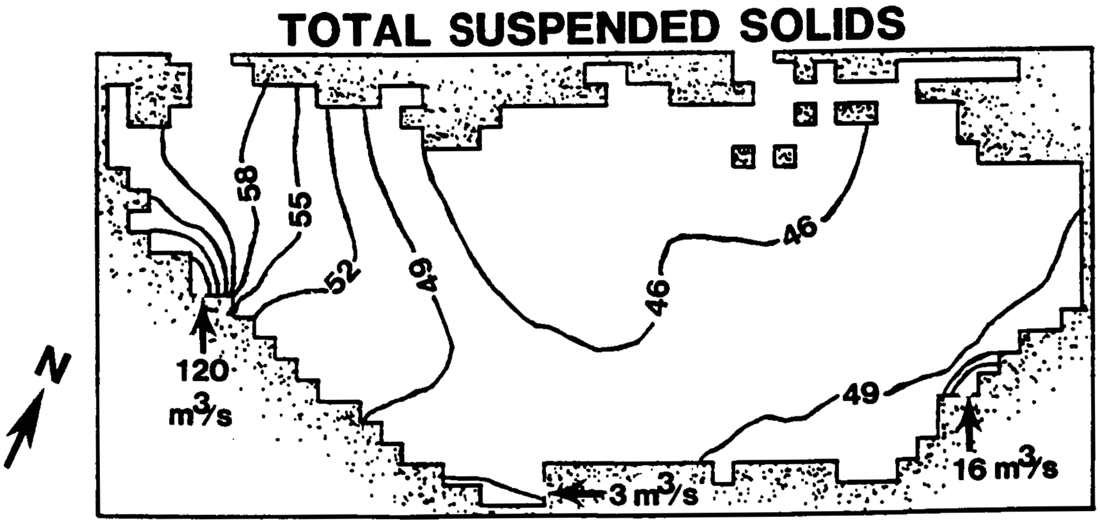

TOTAL SUSPENDED SOLIDS
58
55
52
49
46
46
49
120 m3/s
3 m3/s
16 m3/s
N

Fig 4-A,B

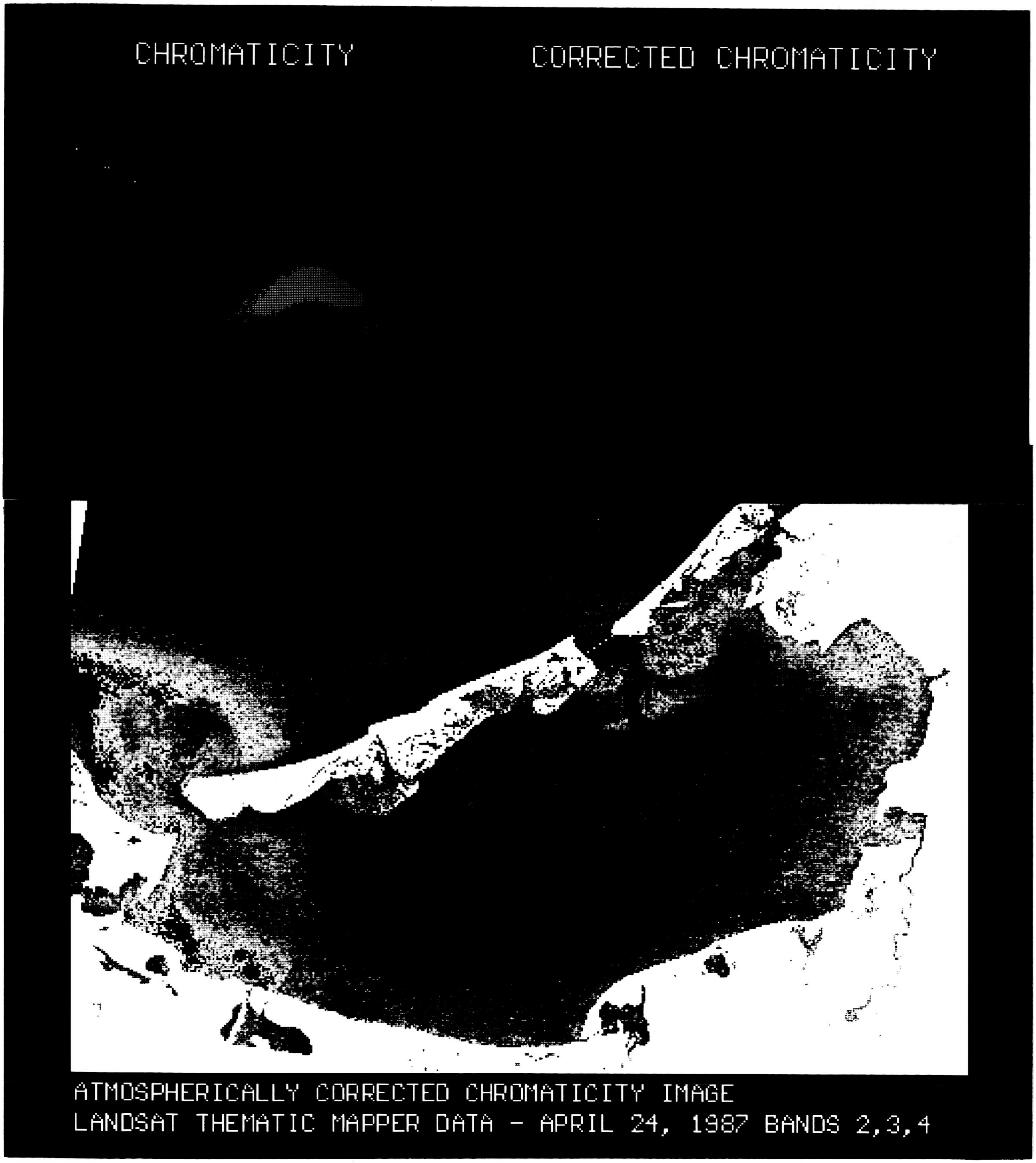
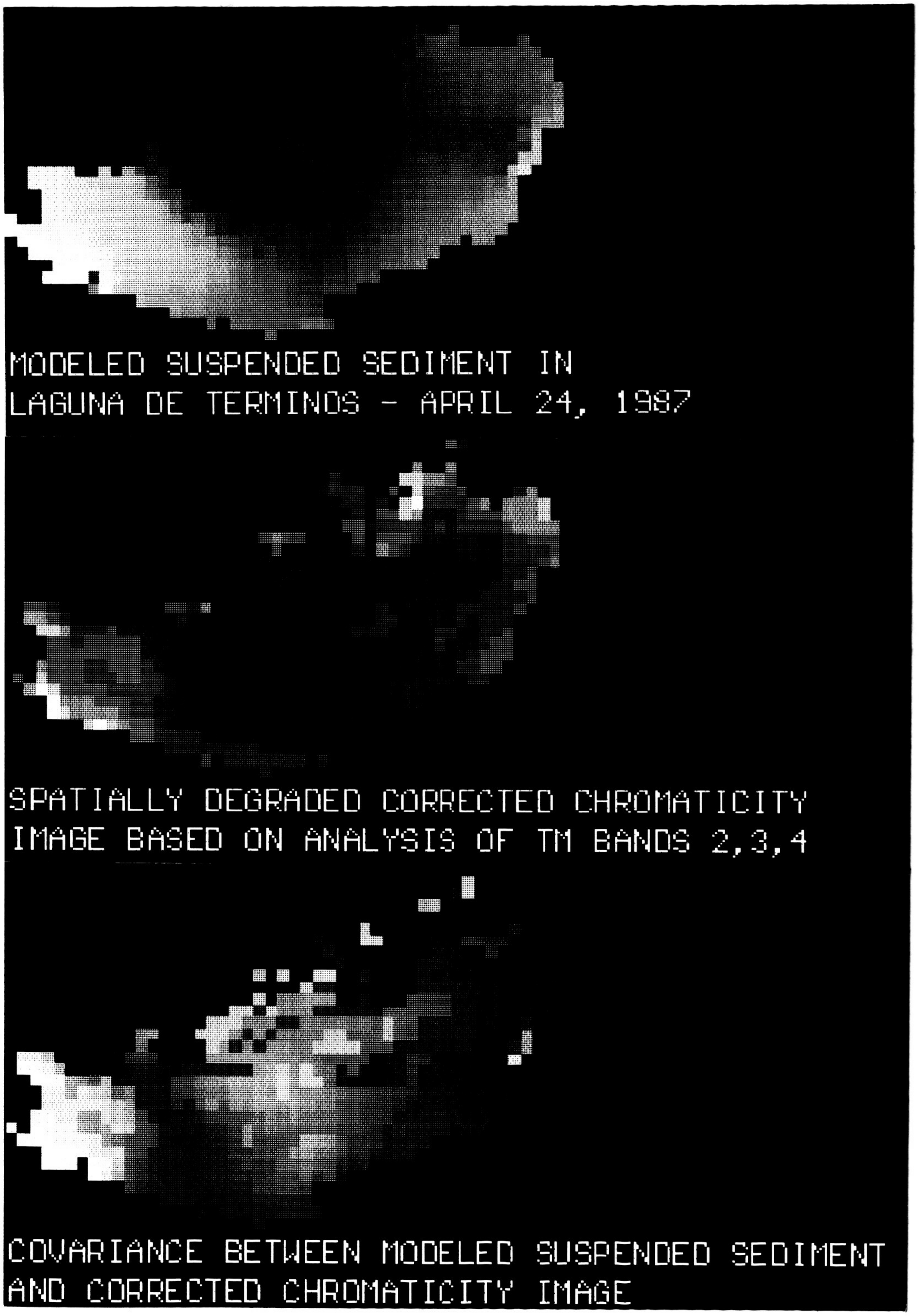

CHROMATICITY
CORRECTED CHROMATICITY
ATMOSPHERICALLY CORRECTED CHROMATICITY IMAGE
LANDSAT THEMATIC MAPPER DATA - APRIL 24, 1987 BANDS 2,3,4

Fig 5 - A,B,C



MODELED SUSPENDED SEDIMENT IN
LAGUNA DE TERMINOS - APRIL 24, 1987

SPATIALLY DEGRADED CORRECTED CHROMATICITY
IMAGE BASED ON ANALYSIS OF TM BANDS 2,3,4

COVARIANCE BETWEEN MODELED SUSPENDED SEDIMENT
AND CORRECTED CHROMATICITY IMAGE

Fig 6 A,B,C

Scatterplot of Modeled Versus Remotely Sensed Suspended Sediment in Laguna de Terminos, Mexico on April 24, 1987

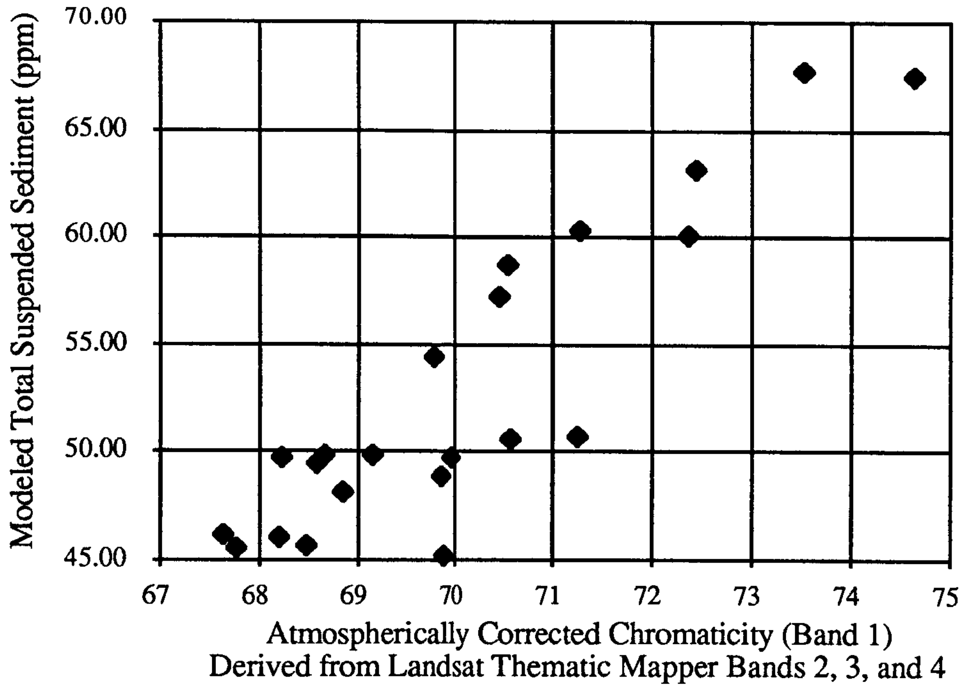


Fig 7